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TO RECENT REGIME SHIFTS**

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## Appendix 2: Recent Ecosystem Changes in the California Current System

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### Summary

*The California Current System (CCS) extends from British Columbia, Canada, to northern Baja California, Mexico. It is a well-studied area and benefits from a comparatively long history of physical and biological observations. Conditions in the CCS are subject to decade-scale regime behavior, with an overlay of episodic warm El Niño and cold La Niña events that last a year or two.*

*In the CCS, there have been strong ecosystem responses to the 1977 and 1989 regime shifts. The 1977 regime shift led to a protracted period of warm surface waters, with a deepening of the thermocline and the implication of lower productivity. However, available zooplankton time series suggest that salp biomass declined after 1977, while euphausiid biomass remained unchanged, and copepod biomass actually increased. Following the 1977 regime shift, overall recruitment improved for species such as Pacific sardine, and other species experienced intermittent very strong year classes (Pacific hake and Pacific cod). After the 1989 regime shift, the warm surface waters intensified and became unproductive for many coastal species. In coastal waters, zooplankton shelf species were replaced by more southerly and oceanic species. Many fish species (Pacific salmon, Pacific hake, Pacific cod, rockfish species) experienced almost a decade of poor recruitment. Southern migratory pelagics (Pacific sardines and Pacific hake) extended the northern limit of their distribution to northern British Columbia, and in some years, to the Gulf of Alaska.*

*After an intense El Niño in 1998, the CCS experienced a very cold La Niña in 1999. Since 1999, sea surface temperatures have tended to return gradually toward warm conditions similar to those in the 1980s and early 1990s, but thermocline depths are now much shallower and nutrient levels are higher, generating higher primary and secondary production. Beginning in 1999, coastal waters saw a return of shelf zooplankton, and many coastal fish stocks experienced substantial improvements in year class success. Some stocks produced good year classes in 1999 (e.g., Pacific hake), and recent returns of several salmon stocks have improved; Columbia River salmon runs have been extraordinary. In addition, the distribution of migratory pelagics (Pacific sardine and Pacific hake) contracted to a more southerly distribution. There is growing evidence, based on a strong and diverse biological response, that a regime shift favoring coastal organisms occurred in 1998.*

### A2.1 Introduction

The California Current System (CCS) extends along the west coast of North America from British Columbia, Canada, to northern Baja California, Mexico. Although this is one of the most thoroughly studied portions of the world's ocean, its properties and dynamics are still not

well understood. During the decade of the 1990s, patterns of low frequency (periodicity greater than 10 years) and large-scale (extent greater than 1000 km) fluctuations in the ocean and atmosphere that appear to have a strong influence on biological productivity of the system, were identified. The CCS exhibits these regimes and regime shifts especially strongly.

## A2.2 Physical Oceanography

The oceanography of the CCS has been relatively well studied, principally because of the long history of the California Cooperative Oceanic Fisheries Investigations (CalCOFI) field survey program (Bograd *et al.* 2003) and a long sampling record off Oregon (Smith *et al.* 2001). The interaction of large-scale circulation of the North Pacific with regional and local forces and factors of the coastal continental boundary controls the circulation and water mass properties of the CCS. The surface flow, the California Current, is the southward-flowing, eastern segment of the clockwise North Pacific Gyre, receiving cool, low-salinity, nutrient-rich water from the North Pacific Current off Oregon, Washington, and southern British Columbia (about 45°–50°N). It terminates off Baja California where it feeds the offshore-flowing component of the Gyre.

Most of the large-scale southward flow occurs in the upper 200 m of the ocean. The California Undercurrent is a warm, high-salinity, low-oxygen poleward flow that lies along the continental slope centered at about 250–300 m depth. Hickey (1979, 1998) and Huyer (1983) provide detailed reviews of the CCS circulation and physical state.

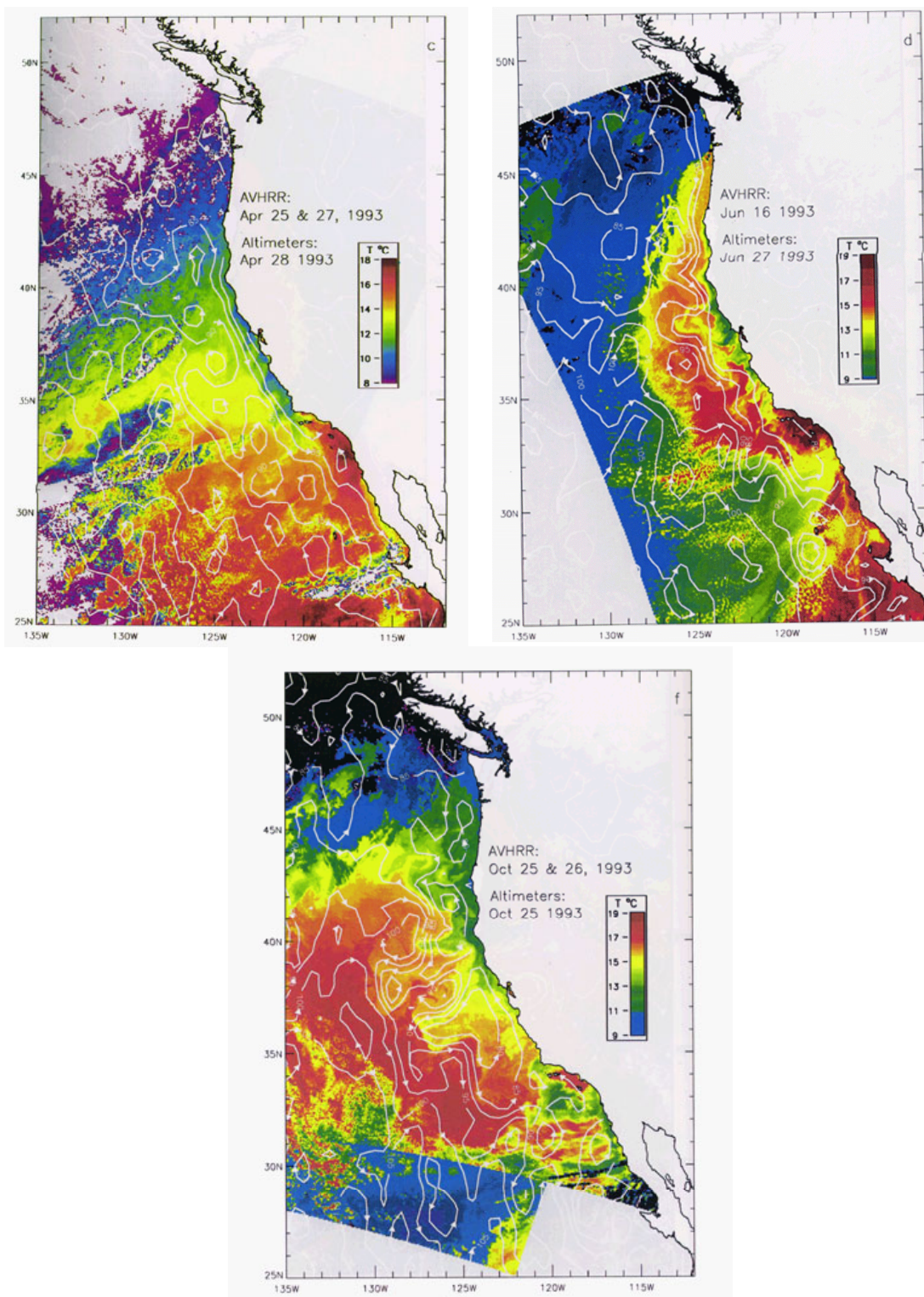
The CCS features a strong annual signal that is predominantly a result of seasonal shifts in large-scale atmospheric forcing. In spring, winds from the northwest establish persistent strong coastal upwelling, which continues into the fall (Fig. A2.1). As a result, an equatorward coastal jet develops in spring, which moves offshore and develops meanders (Strub and James 2000). The greatest seasonal eddy kinetic energy, and most complex physical environment in terms of fronts and eddies, occurs in late summer and fall. The California Undercurrent shoals in late fall – at the time that upwelling-favorable winds slacken or become predominantly northward – and appears as a surface current, called the Inshore Countercurrent, or Davidson Current, in winter (Lynn and Simpson 1987). However, nearshore poleward flows can be found locally off central California most of the year (Yoklavich *et al.* 1997; Steger *et al.* 2000).

While the general transport of the CCS is

southward, local variability in the flow is strongly influenced by coastal processes. These include coastal topography and submarine bathymetry, local heterogeneity in wind forcing, and local freshwater inputs. The most notable, and well studied, interruption in the generally southward flow is the Southern California Bight which features a predominant clockwise circulation and a distinct coastal countercurrent. On a more local scale, headlands and capes determine sites of strong upwelling and upwelling filaments (Kelly 1985; Brink and Cowles 1991; Rosenfeld *et al.* 1994).

The seasonal cycle is superimposed on significant interannual and longer variability. One of the most important sources of interannual variability is the El Niño–La Niña forcing that originates in the equatorial Pacific (Enfield and Allen 1980; Chelton *et al.* 1982; Strub and James 2002). The earliest recognition of their extratropical impacts was identified in the CCS following the 1957–58 El Niño event (Sette and Isaacs 1960). However, the signal of individual El Niños in the CCS varies (Schwing *et al.* 2002; Mendelssohn *et al.* 2003). Some events have a strong subsurface signal indicative of an equatorial origin that is transmitted via coastal ocean waves. Others are predominantly a near-surface signal, suggesting that these El Niños affect the CCS primarily via atmospheric teleconnections and alterations of the CCS by local atmospheric forcing. These patterns of spatial separation could affect populations differently, depending on their preferred habitat.

The upper ocean response to climate forcing in the CCS is also partitioned laterally and vertically (Fig. A2.2). Based on its physical character, the CCS can be separated into three distinct regions, which correspond to biogeographic provinces separated by Cape Mendocino and Point Conception (Parrish *et al.* 1983). These regions feature distinctly differing climatologies. The long-term climate shifts also are reflected differently in these regions, presumably because the dominant physics of each region interacts with large-scale climate signals (Schwing *et al.* 1998). For example, the central CCS region, which is dominated by coastal upwelling, has shown a tendency for increased spring–summer upwelling over the past 50 years that is not evident to the



**Fig. A2.1** Snapshots of altimeter sea surface height fields (contours) and Advanced Very High Resolution Radiometer (AVHRR) sea surface temperature (SST) (color) representing California Current System (CCS) spring, summer and fall conditions (from Strub and James 2000).

north or south (Schwing and Mendelssohn 1997). Ocean temperatures to the north, and within the thermocline, began warming several years prior to the often-cited 1976 regime shift (Fig. A2.2).

The CCS has displayed a long-term warming tendency throughout its extent (Roemmich and McGowan 1995; Mendelssohn *et al.* 2003). In addition, long-term increases in stratification and a deepening of the thermocline in the coastal CCS over the past 50 years (Palacios *et al.* 2004) imply that nutrient input to the photic layer and overall productivity has declined over time (Roemmich and McGowan 1995). The magnitude and timing of the seasonal cycle of upper ocean temperature, thermocline strength and depth vary as well (Mendelssohn *et al.* 2004; Palacios *et al.* 2004), potentially affecting the ambient conditions for seasonal upwelling and the timing of biological cycles.

Decadal-scale sea surface temperature (SST) variations in the CCS are strongly coupled with basin- to global-scale atmospheric fields, rather than to local wind forcing (Parrish *et al.* 2000). Interannual, decadal and longer-term fluctuations in the CCS are approximately synchronous with other eastern boundary current systems, demonstrating that global processes interacting with local dynamics are responsible for much of the long-term variability in the CCS – including regime shifts. For example, the CCS and Humboldt Current regions, with similar dynamics (*e.g.*, strong coastal upwelling zones), display corresponding long-term wind and SST trends, indicating that global climate variability contributes to geographically distinct regime shift responses (Mendelssohn and Schwing 2002).

The spatially distinct responses to regime shifts and long-term climate change are likely to lead to different impacts on marine populations, depending on the CCS regions and depths they exploit. For organisms that inhabit different regions at different life stages (larval *versus* adult), or during key life strategies (migration, reproduction), this may provide a clue about which of these biological aspects are most sensitive to climate variability.

## A2.3 Lower Trophic Levels

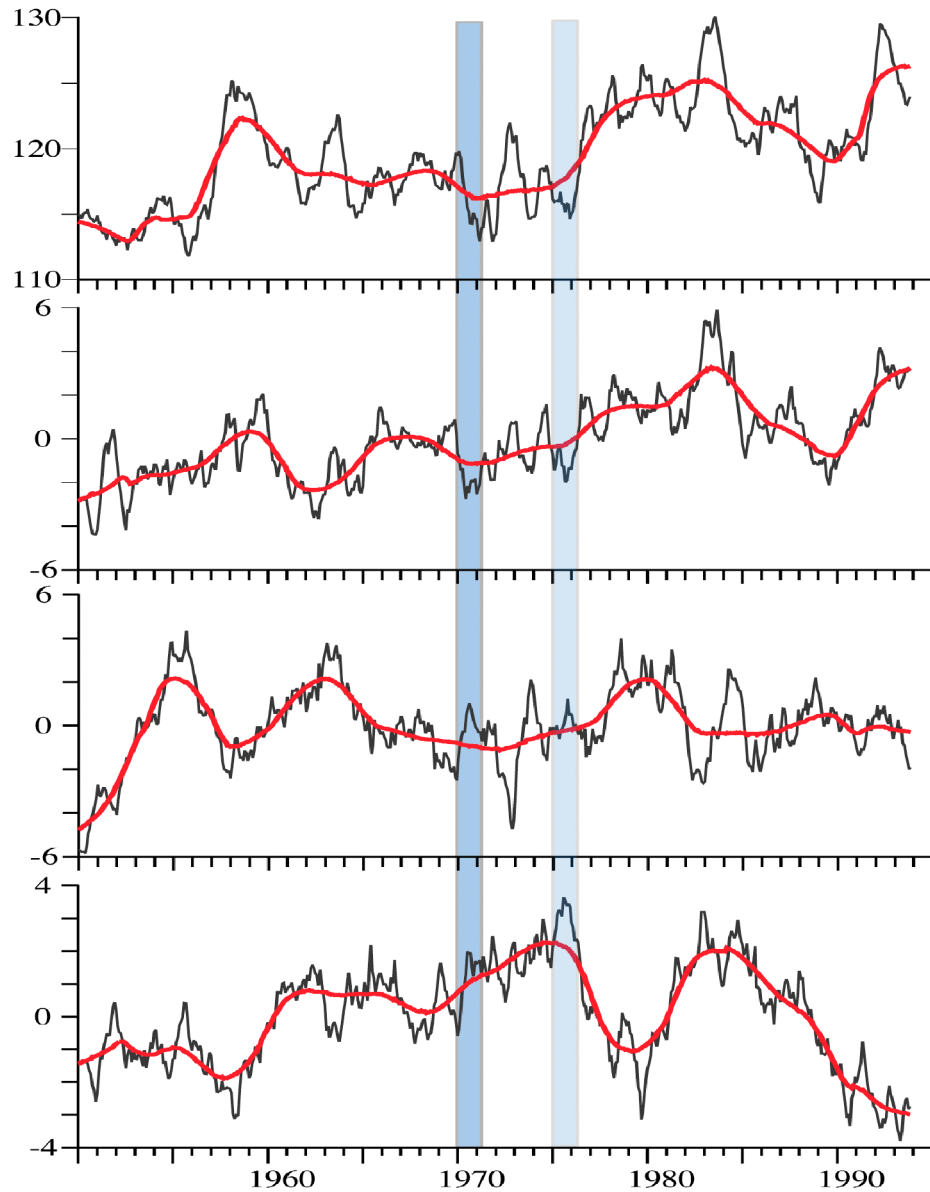
### Phytoplankton and pigment concentration

For various reasons, there is less information available about possible phytoplankton regime shifts in the CCS. Part of the problem is difficulty of sampling – phytoplankton populations can bloom very rapidly and locally in the CCS, so data series must be very densely spaced to avoid the aliasing of high frequency variability. In more slowly varying offshore populations, Venrick *et al.* (1987) showed a strong upward trend in Central Gyre chlorophyll concentration from 1964–85, with the strongest change near 1975. Within the CCS, the best hope for time series is from sequential satellite mapping of ocean color. Two non-overlapping time series are now available:

1. CZCS (Coastal Zone Color Scanner) 1978–86, and
2. SeaWiFS (Sea-viewing Wide Field-of-view Sensor) 1997–present.

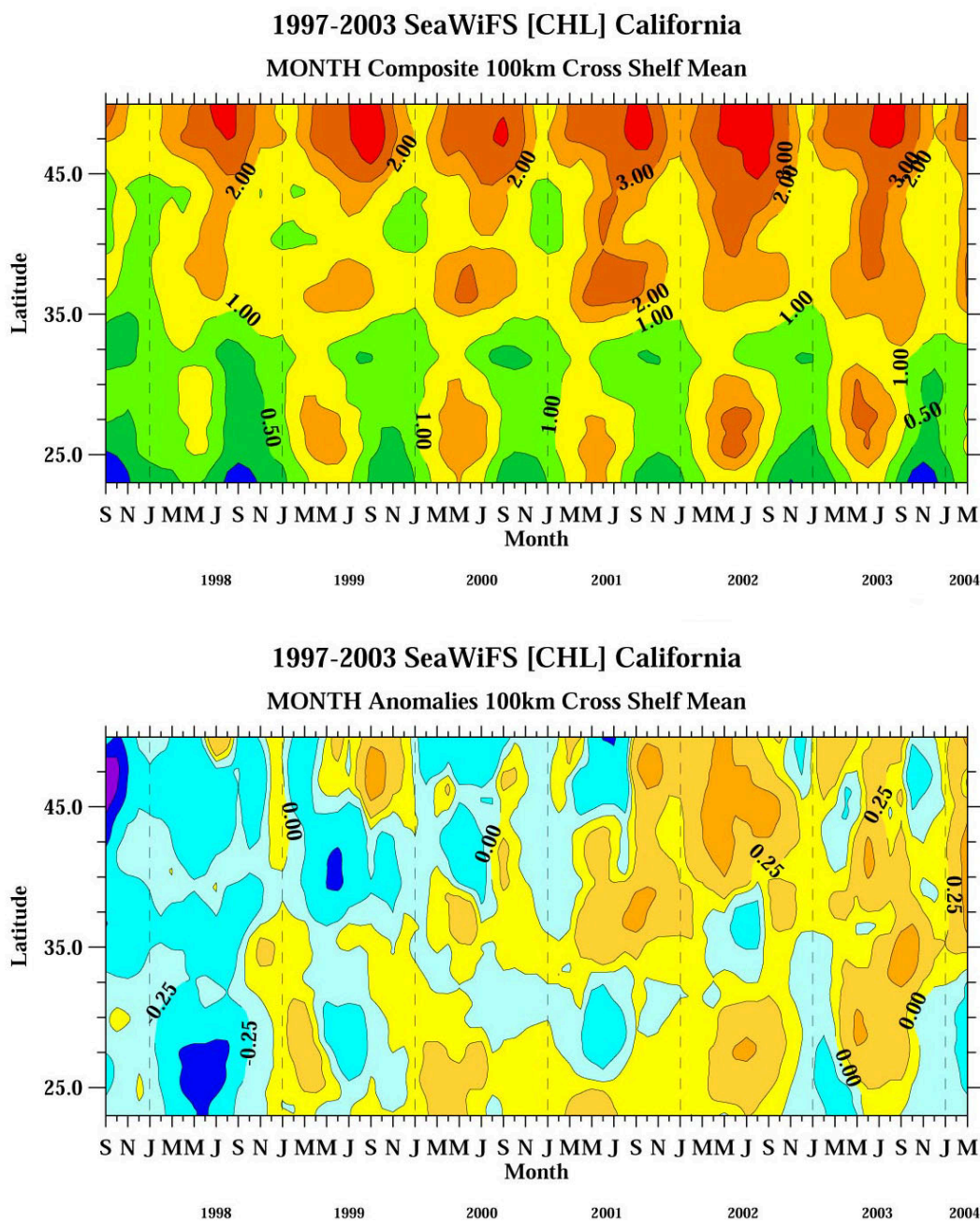
Neither period captures the hypothesized 1977 and 1989–90 regime shifts, and the two data sets are not fully intercomparable. However, the recent 1998–99 period was resolved extremely well. Average pigment concentration 0–100 km from the coast increased after 1998 throughout the CCS (Fig. A2.3), and the margin of the zone of high pigment concentration also moved farther offshore (Thomas *et al.* 2001).

Information about changes in phytoplankton species composition within the CCS is potentially available for some taxa (mostly larger species with hard cell walls). A long time series of phytoplankton cell counts has been collected from the Scripps Pier, but has not been fully analyzed and interpreted. Varved sediment columns from anoxic basins in, and near, the CCS provide a potentially very long time record, but must be interpreted with care due to selective and time-cumulative dissolution of microfossils. Sancetta (1995) reports records from the Gulf of California, and McQuoid and Hobson (2001) from Saanich Inlet, British Columbia.



**Fig. A2.2** Time series of common trends (top to bottom) of California Current System (CCS) ocean temperature, based on 110 time series. The first trend is the system tendency for warming, with El Niño–Southern Oscillation (ENSO) and regime shifts superimposed. The second trend is a cross-shore mode, with coastal locations having a stronger impact from ENSO and decadal events. The third trend is an alongshore mode, showing ENSO events with a greater northern extent. The fourth trend is a depth mode, showing trends in stratification. Blue vertical bars highlight 1970 and 1976 to contrast differences in the 1970s regime shift in different geographical domains of the CCS (adapted from Mendelssohn *et al.* 2003).





**Fig. A2.3** SeaWiFS latitude vs. monthly records of average chlorophyll concentration (top panel) and anomalies from the average seasonal cycle (bottom panel) during and after the 1998–99 interval. Chlorophyll estimates are averaged within each month and across the 0–100 km zone extending seaward from the coast. After 1998, zones of low pigment concentration became briefer and narrower; zones of high pigment concentration became more prolonged and extensive (updated and extended from Thomas *et al.* 2001; courtesy, A. Thomas).

## Zooplankton

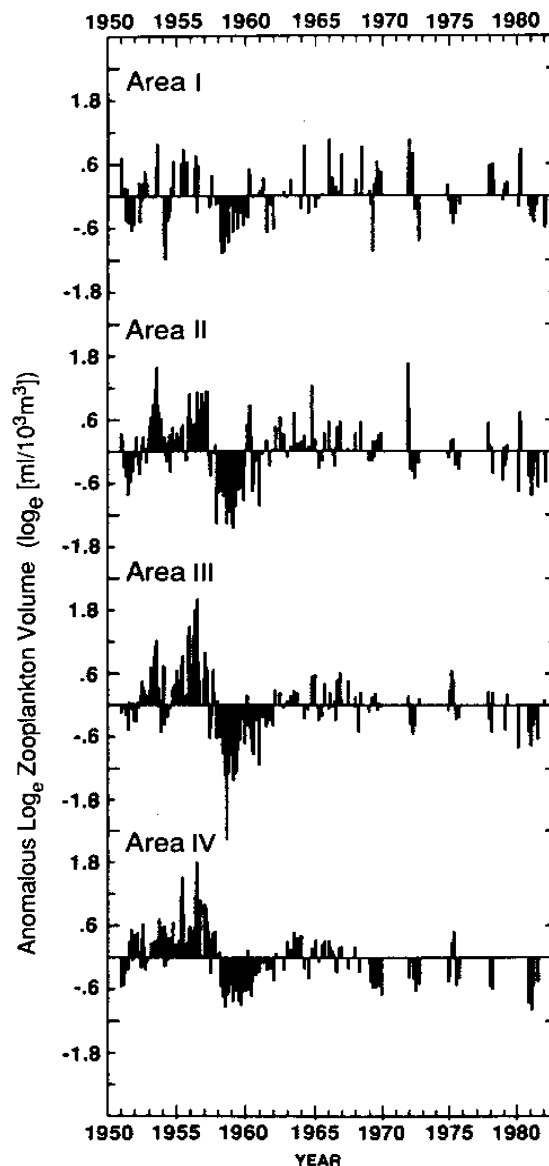
Long-term (>20 years) records of zooplankton biomass and community composition in the CCS are available from central-southern California (CalCOFI 1950–present), southern Vancouver Island (1979–present), and central Oregon (1969–73, 1983, and 1996–2001). Collectively, they provide strong evidence that zooplankton variability at decadal time scales is:

- intense (order of magnitude typical range);
- coherent in form over the full width of the CCS and over alongshore distances >400 km;
- sometimes abrupt, with major transitions between high and low abundance matching within  $\pm 1$  year the “regime shift” dates identified from climate and fisheries indices;
- coherent in the *timing* of transitions, perhaps extending the full alongshore length of the CCS, and poleward into the Alaska Current system.

Data from the CalCOFI region are summarized in Figures A2.4 and A2.5, and from British Columbia and Oregon in Figure A2.6. In all three regions, the zooplankton time series show large and persistent deviations from local average annual cycles. Runs of higher-than-average or lower-than-average abundance typically persist for 5–10 years or longer (*vs.* the 1- to 2-year duration of individual ENSO events).

For the CalCOFI region, the earliest analyses (Fig. A2.4) were by Bernal (1979, 1981), Bernal and McGowan (1981), Chelton *et al.* (1982), and Roessler and Chelton (1987). These covered data from 1951–82, and were mostly confined to zooplankton biomass. (Roessler and Chelton (1987) added a brief discussion of 1958 anomalies in alongshore species distributions.) In each of the four alongshore sub-regions extending from San Francisco Bay to southern Baja California, zooplankton biomass from 1950–57 was very high, and from 1958–62, very low. From 1962–82, biomass was initially high but became anomalously low part way through the 1970s (earlier off southern Baja California; later off central California). Higher biomass was significantly correlated with various indices of stronger equatorward flow in the California

Current (low coastal sea level, cross-shore dynamic height gradient, low temperature, low salinity). However, much of the total variance (especially in the physical data) was associated with the start of the 1958 El Niño event.



**Fig. A2.4** 1951–82 time series of zooplankton biomass anomalies in four regions of the CCS. Regions are arranged from north to south: (I) San Francisco to Point Conception, (II) Point Conception to San Diego, (III) Baja California (San Diego to Puente Eugenia), (IV) Baja California Sur (Puente Eugenia to Isla Magdalena). Note the strong alongshore covariance over an alongshore distance of nearly 1500 km (from Roessler and Chelton 1987).



Subsequent CalCOFI sampling and analyses have been restricted to the alongshore zone between Point Conception and San Diego (30°–35°N). Results are summarized in Figure A2.5. Roemmich and McGowan (1995) and McGowan *et al.* (2003) showed that a prolonged downward trend in total zooplankton biomass began in the mid-1970s (perhaps in 1976) and continued through to 1998. This decline affected the full width of the California Current (Fig. A2.5) but was more strongly correlated with sea surface warming and an increase in vertical stratification, rather than with either upwelling intensity or transport variability. However, taxonomically-resolved time series for the CalCOFI region (side bars in Fig. A2.5) have been produced for pelagic tunicates (Lavaniegos and Ohman 2003), copepods (Rebstock 2001, 2002, 2003) and euphausiids (Brinton and Townsend 2003), and these time series indicate that the overall decline in total zooplankton biomass was driven by long-term declines in the biomass of pelagic tunicates. Lavaniegos and Ohman (2003) documented a major decline in abundance of some (but not all) salp species after the mid-1970s, and a subsequent increase in abundance since 1999. Rebstock (2001, 2002, 2003) found that the copepod dominance hierarchy was stable (nearly always dominated by *Calanus pacificus* and *Metridia pacifica*). Strong El Niño conditions during the late 1950s and early 1980s affected copepod abundance (Rebstock 2002). The 1977 regime shift resulted in an increase in abundance of calanoid copepods, and the 1989 regime shift corresponded to a decrease in copepod abundance around 1990 (Rebstock 2002). Subsequent observations support an additional large increase in copepod abundance in 1998–99. Large changes in euphausiid community composition have been observed, with subtropical species increasing in dominance since the late 1970s, but from 1999 to at least 2002, there has been a return to dominance of subarctic euphausiid species (Brinton and Townsend 2003). Unlike pelagic tunicates and calanoid copepods, there does not appear to be any significant changes in euphausiid abundance across regime periods (Brinton and Townsend 2003).

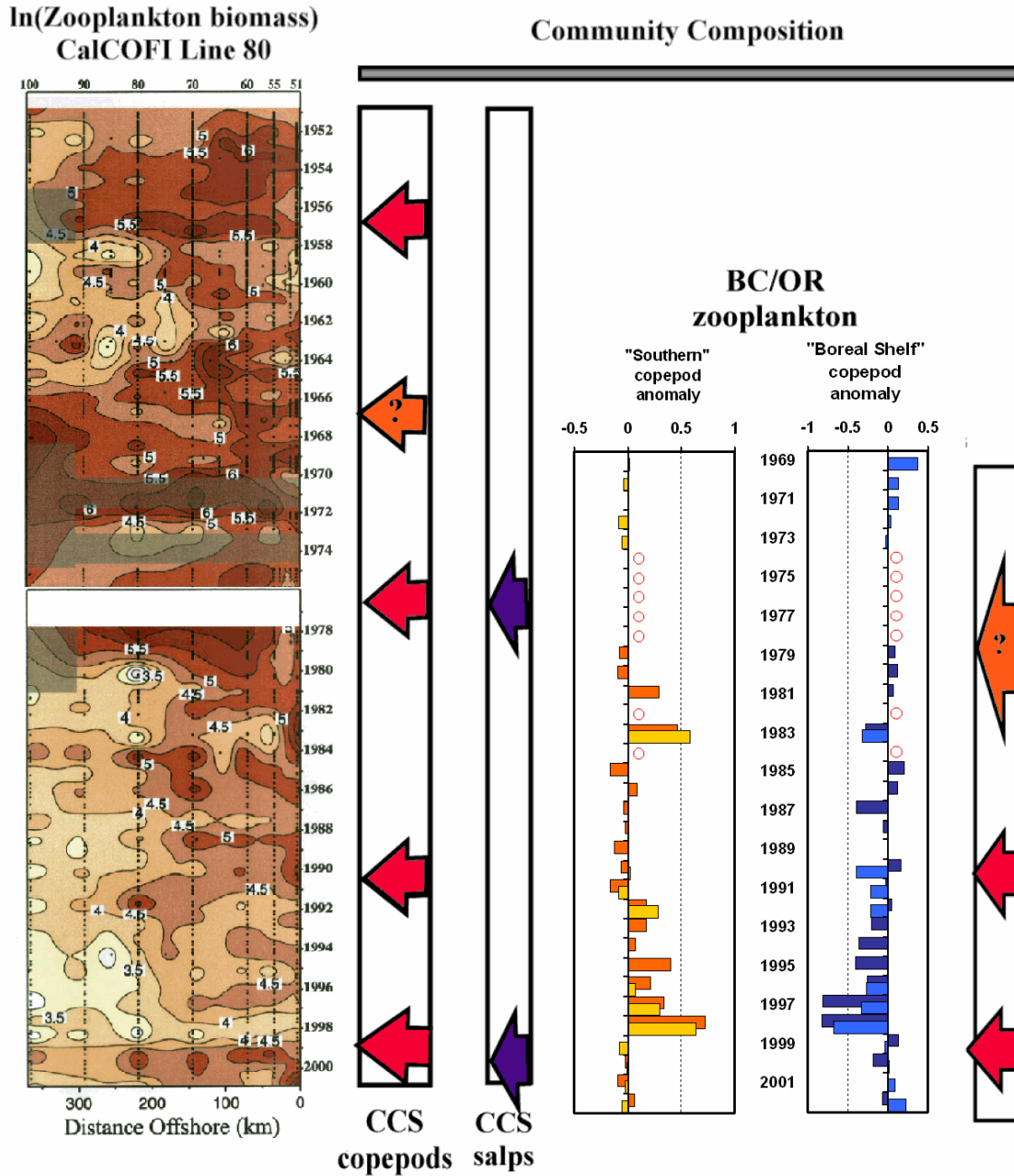
Data from the British Columbia and Oregon

continental margins (Fig. A2.6, plus far right sidebar in Figure A2.5) show very strong spatial and temporal covariance within groups of ecologically similar species. The most striking result was a partial to near-complete replacement, during the 1990s, of the resident continental shelf copepod community (dominated by *Calanus marshallae*, *Pseudocalanus mimus*, and *Acartia longiremis*) by species “normally” abundant off central and southern California (*Clausocalanus* spp., *Paracalanus parvus*, and *Ctenocalanus vanus*). This trend abruptly reversed during the 1997–99 El Niño–La Niña, and since 1999 the zooplankton community has resembled the average for the 1970s–80s.

#### A2.4 Invertebrates

Significant changes in species composition have been observed when large-scale ecosystem reorganizations have occurred. Globally, Caddy and Rodhouse (1998) noted that as groundfish stocks have declined, they appear to have been replaced by increases in cephalopod populations. In the coastal Gulf of Alaska, a switch from a crustacean- to a groundfish-dominated system was observed, following the regime shift of the late 1970s (Anderson and Piatt 1999). In the Northwest Atlantic, there was a significant change in species composition following the collapse of the northern cod stock, but in contrast to that in the Gulf of Alaska, the shift in the Northwest Atlantic was from a groundfish- to a crustacean-dominated system.

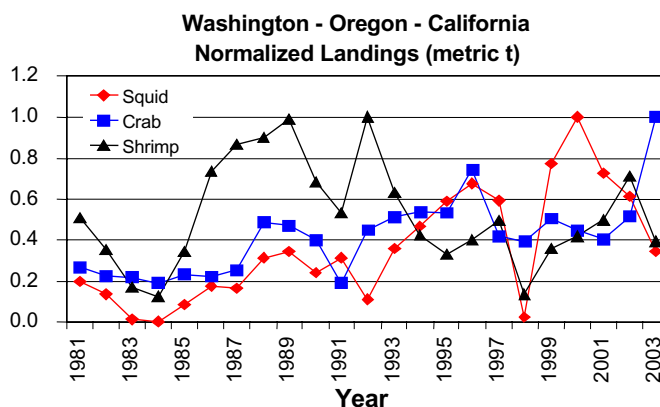
In California, the top three most valuable fisheries (as landed value) have recently been market squid (*Loligo opalescens*), sea urchin (*Strongylocentrotus franciscanus*) and Pacific Ocean shrimp (*Pandalus jordani*) (Rogers-Bennett 2002). Dungeness crab (*Cancer magister*) has long been a commercially important invertebrate in Washington and Oregon. Landings of market squid, Dungeness crab, and Pacific Ocean shrimp in California, Oregon and Washington since 1981 show marked declines in 1983 and 1998, corresponding to the strong El Niño events of those years; they also illustrate the increasing trend in landings over time for squid as the fishery developed (Fig. A2.6).



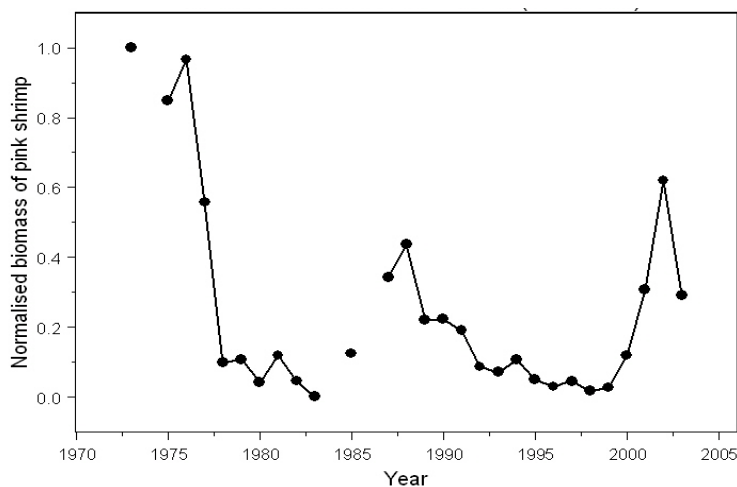
**Fig. A2.5** Zooplankton biomass and community variability in the California Current System (CCS), 1952 to present. Contour plot in left panel shows cross-shore time series of zooplankton biomass for CalCOFI Line 80 (near Point Conception). Right hand side bars show timing match with transitions (indicated by arrows) in CalCOFI, British Columbia, and Oregon zooplankton species abundance/community composition. Data from multiple sources: CCS copepods from Rebstock (2001, 2002, 2003; red) and updated data (Ohman, pers. comm.), CCS salps from Lavaniegos and Ohman (2003), British Columbia/Oregon zooplankton from Mackas *et al.* (2004). Arrows with a question mark denote transitions that are uncertain, either due to changes in sampling protocol (CCS copepods) or lack of data (British Columbia/Oregon zooplankton) (from Mackas 2004).

The recent decline in landings of squid (dominated by California) and the increases in landings of Dungeness crab (dominated by Washington and Oregon) suggest a possible change in the fisheries since 2001. It should be noted that these crab populations appear to cycle in abundance, with peaks and troughs every 8–10 years (Otto and Jamieson 2001). Landings of shrimp (dominated by Washington and Oregon) have been increasing since the 1998 El Niño and the return of cool water in 1999. This recovery of ocean shrimp populations in the CCS is corroborated by fishery-independent shrimp surveys conducted off

southern Vancouver Island at the northern end of the California Current (Fig. A2.7). The population biomass estimated from these surveys was highest in the mid-1970s prior to the 1977 regime shift, with a local maximum in 2002 after increasing since 2000, consistent with an expectation that this shrimp species does better with cooler conditions. Note there was a decrease in the population biomass off Vancouver Island (Fig. A2.7) and in Washington–Oregon landings (Fig. A2.6) in 2003, coinciding with warmer conditions of a mild ENSO event in late 2002.



**Fig. A2.6** Washington/Oregon/California landings of market squid (*Loligo opalescens*), Dungeness crab (*Cancer magister*) and Pacific Ocean shrimp (*Pandalus jordani*). Values have been normalized to the maximum value in the data series for each species. Data are from the Pacific Fisheries Information Network (PacFIN) database maintained by the Pacific States Marine Fisheries Commission ([www.psmfc.org](http://www.psmfc.org)).



**Fig. A2.7** Fishery-independent survey estimates of population biomass of *Pandalus jordani* (Pacific Ocean shrimp or smooth pink shrimp) for the southern continental shelf of Vancouver Island, British Columbia, at the northern end of the California Current system. Values have been normalized to the maximum value in the data series.

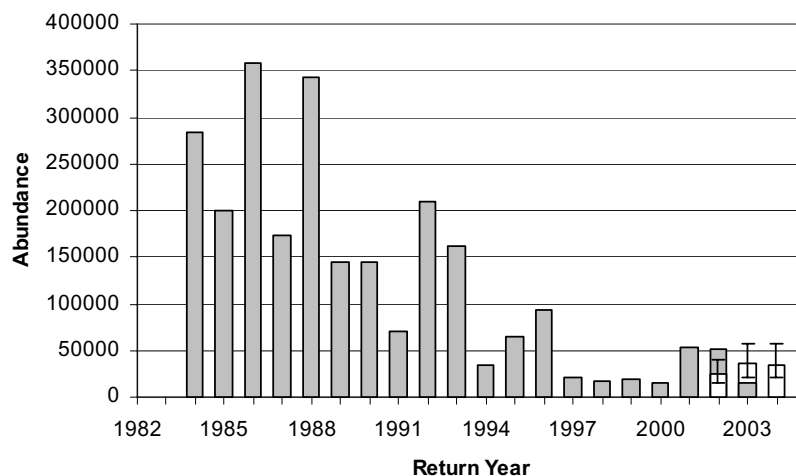
## A2.5 Fishes

### Pelagics

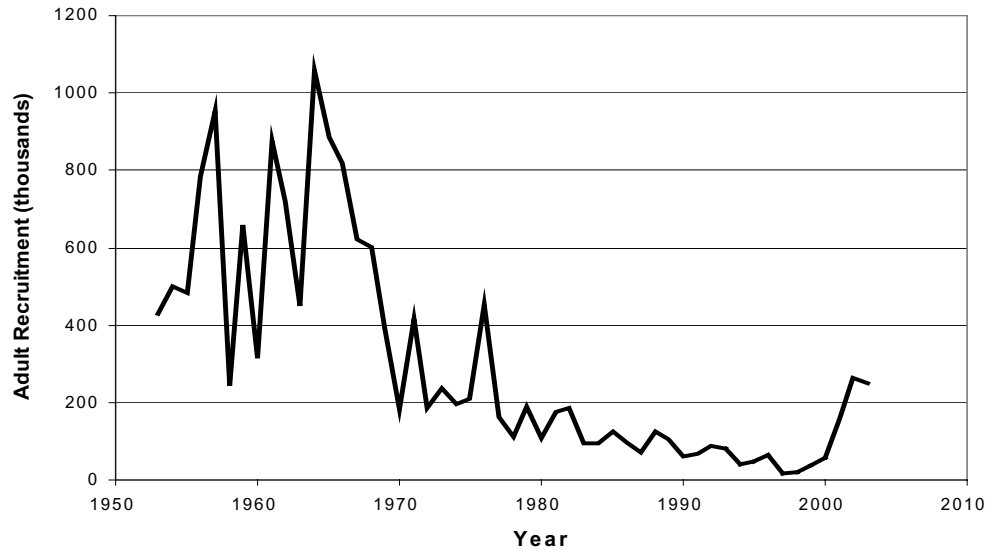
#### Coho salmon (*Oncorhynchus kisutch*)

Coho salmon are one of seven species of the genus *Oncorhynchus* native to North America and are distributed from the Bering Sea as far south as the Sacramento River system in California (see Sandercock (1991) for a review). Coho salmon are anadromous, migrating to the marine environment in the spring as smolts, and returning to freshwater in the fall and early winter of their third year to spawn and die. Fry emerge from the gravel in the following spring and usually reside in freshwater for a year before migrating to sea as smolts. Almost all coho spend 18 months at sea before returning to freshwater and therefore have a 3-year life cycle. Jacks (precocious males), which spend only 6 months in the ocean, are found in some populations. Adult coho usually weigh from 2–5 kg (45–70 cm in length) and only rarely exceed 9 kg. Coho favor smaller streams and are widely dispersed within the northern portion of the California Current ecosystem. The Fraser River is the largest river in British Columbia, and the interior Fraser (*i.e.*, upstream of the Fraser canyon) constitutes most of the drainage basin. Interior Fraser coho occupy a significant proportion (~25%) of the range of coho salmon within Canada. Estimates of coho abundance for this region indicate a substantial decline in abundance from the early 1980s to the present (Fig. A2.8,

from Simpson *et al.* 2004). It is believed that reduced survival in the marine environment has been the main determinant of recent reduced population abundance. Overfishing, changing marine conditions, and habitat perturbations all contributed to declines (Bradford and Irvine 2000; Bradford 1999). Excessive fishing resulted when harvest rates were not reduced quickly enough in response to climate-driven declines in marine productivity. In addition, coho declines were often related to the intensity of human disturbance in freshwater, whereby extensive urbanization has impacted available spawning habitats through stream destruction or watershed impacts from upstream logging operations. Comparable declines in coho marine survival have been noted in the Strait of Georgia, Puget Sound and in the Oregon coho production index (Beamish *et al.* 2001a). All three indices suggest a long-term decline in coho survival, beginning in the mid-1970s. However, recent improvement in the Oregon coho production index implies that conditions have changed since 1999 (Fig. A2.9). Beamish *et al.* (1999, 2001a) suggest that the reduction in survival is related to a number of changes in the oceanic environment, particularly the Aleutian Low Pressure Index (ALPI) which may have reduced the available food supply of coho smolts, leading to increased overwinter mortality. In addition, in the Strait of Georgia there may have been increased competition for food with Pacific herring during the first year in the ocean, again impacting coho survival (Beamish *et al.* 2001b).



**Fig. A2.8** Estimated abundance of Thompson River, British Columbia, watershed coho from 1984 to 2003. The forecasts for 2002–04 are shown as clear bars with associated 50% confidence intervals.



**Fig. A2.9** Adult recruitment estimates for Oregon Production Index coho salmon. Data were provided by the Oregon Department of Fisheries and Wildlife, Oregon Production Index Technical Team.

#### Columbia River salmon (*Oncorhynchus* spp.)

The Columbia River experienced very low returns for many salmon species or stocks during the 1990s, while relatively high values were recorded for spring and fall chinook (*O. tshawytscha*), coho, sockeye (*O. nerka*), and summer steelhead (*O. mykiss*) in the mid-1980s and again in 1999, 2000, and 2001 (Fig. A2.10). Data for 2002 and 2003 (not shown) include continued high returns for spring, summer, and fall chinook, and summer steelhead. Spring chinook returns for 2004 were about 190,000 fish, well above the 10-year average and comparable to returns typically observed in the 1980s. From 1940 to the mid-1990s, there was an inverse relationship between Alaskan catches of sockeye and pink salmon (*O. gorbuscha*) and Columbia River spring chinook returns (Fig. A2.11). Since the late 1990s, values have been high for both groups.

#### Pacific herring (*Clupea pallasii*)

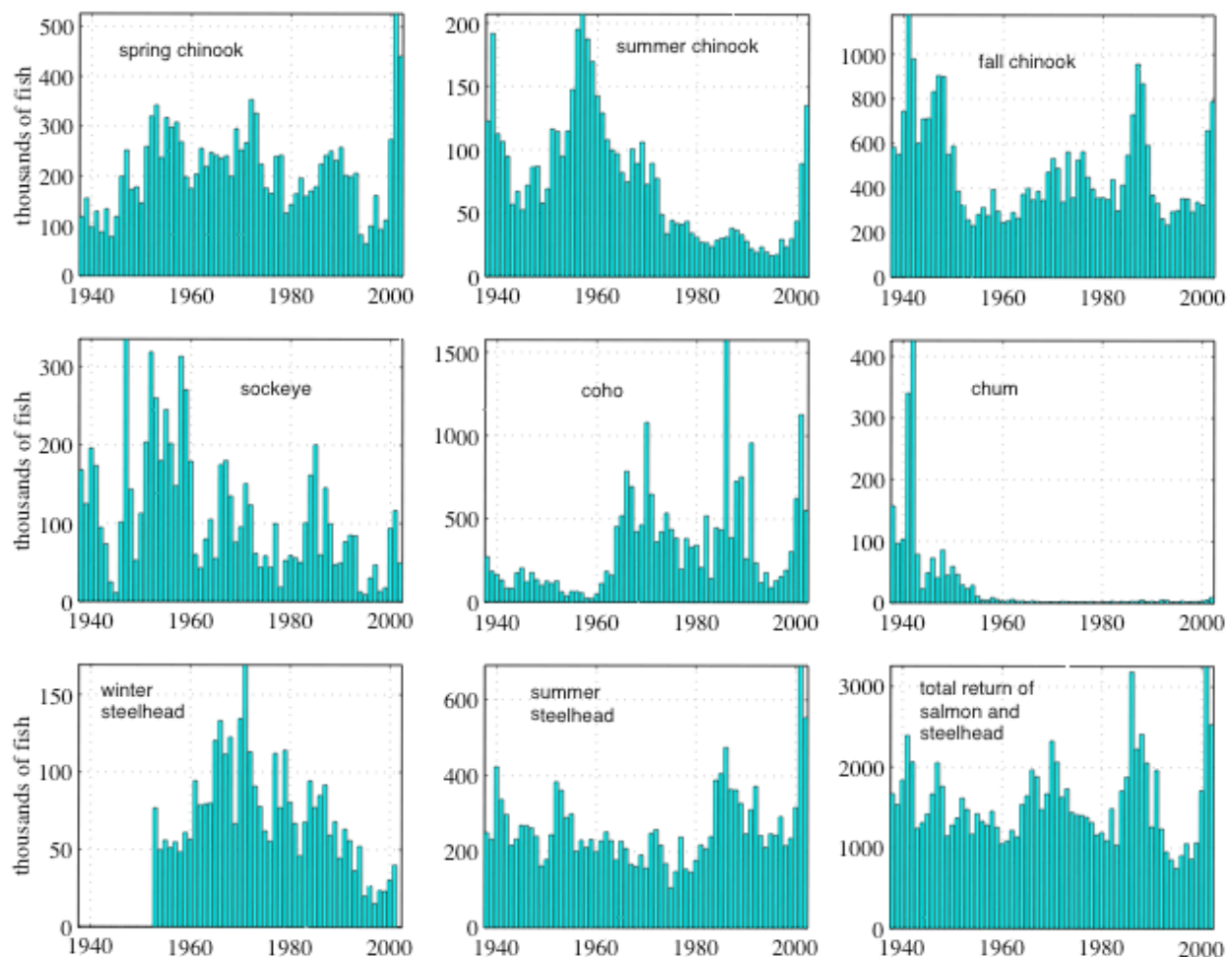
Pacific herring are distributed around the perimeter of the North Pacific, from the Yellow Sea in Asia, to southern California (Haegele and Schweigert 1985). They are intertidal spring spawners throughout the range, laying adhesive eggs on any available algal substrates, and so depend on suitable inshore habitat at the beginning of their life cycle. The eggs hatch into free-floating larvae within 2–3 weeks, depending on

ambient water temperature. Juveniles spend their first summer in inshore waters feeding on copepods, then migrate offshore to join immature and adult stocks during the fall of their first year or late spring of their second summer. In general, herring migrate back to their spawning areas for the first time at age 3 in the south and age 4 in the north. Herring in the eastern Pacific normally live to ages less than 10 years, although fish as old as age 15 have been taken historically in some areas.

The California Current ecosystem supports a substantial number of herring stocks. Numerous minor herring stocks exist between San Diego and Vancouver Island, including Puget Sound. The major stocks in this ecosystem are found in San Francisco Bay, on the west coast of Vancouver Island (WCVI), and within the Strait of Georgia. Herring abundance within the San Francisco Bay area has fluctuated dramatically from very high levels, exceeding 100,000 tons in the early 1980s, to less than 20,000 tons in recent years (Watters, pers. comm.; Fig. A2.12). No clear explanations for the decline are evident but negative impacts of the strong 1982–83 El Niño on herring growth and survival have been noted (Spratt 1987). Within the northern part of this current system, a number of small stocks occur within Puget Sound, and these have remained at relatively stable levels, with the exception of Cherry Point, which has

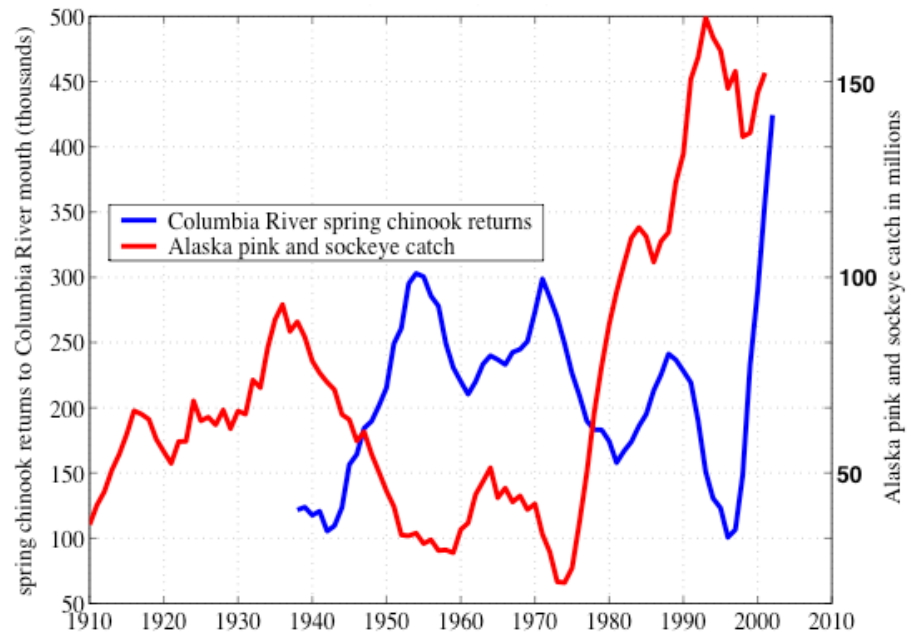
declined dramatically since the early 1980s when it was impacted by a significant roe fishery. Despite fishery closures, the stock has not recovered. The other two major herring stocks at the northern edge of this ecosystem spawn on the WCVI and in the Strait of Georgia (Schweigert 2001). After being decimated by a reduction fishery in the late 1960s, both stocks recovered to high levels of abundance in the early 1970s, approaching 200,000 tons combined (Fig. A2.12). Abundance declined markedly in both areas in the mid-1980s, approaching 50,000 tons, and then increased again. The Strait of Georgia stock has increased almost exponentially, reaching a historical high of over 150,000 tons in recent

years, while the WCVI stock increased to about 50,000 tons in the late 1980s, and has subsequently declined to about 20,000 tons in recent years. Factors affecting the survival and productivity of these stocks are only partially understood. Herring on the WCVI are impacted by hake on the offshore feeding grounds and have shown lower recruitment in years of higher SSTs when it is expected that more hake migrate farther north to feed on immature herring (Ware and McFarlane 1986). However, herring in the Strait of Georgia continue to show good survival rates, and it is suggested that the reduced growth rate of hake has mitigated herring predation by hake in this area (McFarlane *et al.* 2001).

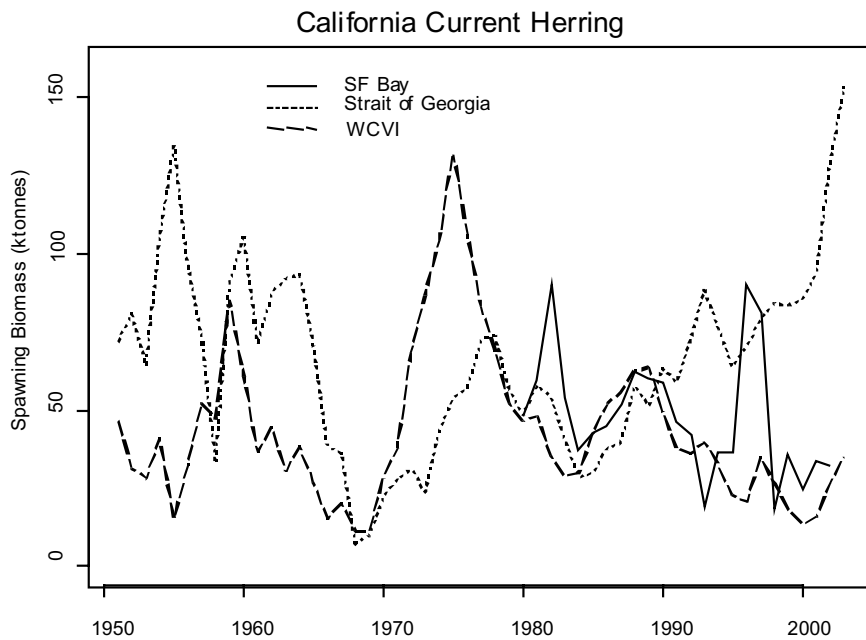


**Fig. A2.10** Minimum estimates for annual adult salmon returns to the Columbia River mouth (lower river catch + counts at Bonneville Dam). Data provided by the Oregon Department of Fish and Wildlife and the Northwest Power Council.





**Fig. A2.11** Comparison of observed Alaska sockeye and pink salmon catches vs. Columbia River spring chinook returns (5-year running averages).



**Fig. A2.12** Abundance trends for three stocks of Pacific herring: San Francisco Bay (SF Bay), Strait of Georgia, and the west coast Vancouver Island (WCVI).

A number of authors have also noted an inverse relationship between herring survival and SST in the northern California Current ecosystem (Ware 1991; Schweigert 1993; Zebdi and Collie 1995; Williams and Quinn II 2000). It appears that this effect occurs primarily in the outer coastal areas and is associated with increased predation, possibly in conjunction with negative impacts on the food supply. Environmental impacts on herring in the more southerly stocks appear to be associated with major El Niño events which affect the food supply, adversely impacting growth rate, and ultimately the survival of herring in San Francisco Bay (Spratt 1987).

#### Pacific sardine (*Sardinops sagax*)

During the twentieth century, Pacific sardine abundance fluctuated from a high of 3 million tons *ca.* 1930, to undetectably low levels in the 1960s and 70s, and back to 1 million tons at the end of the century (Murphy 1966; MacCall 1979; Conser *et al.* 2002). Patterns of sardine scales preserved in laminated anaerobic sediments, representing nearly 2000 years of history, indicate that California's sardines have always been subject to very large fluctuations in abundance (Baumgartner *et al.* 1992). The recent increase in sardine abundance appears to have been associated with post-1976 environmental conditions. Jacobson and MacCall (1995) describe the relationship between sardine recruitment, parental abundance and multi-year average SSTs measured at the Scripps Institution of Oceanography Pier (Fig. A2.13). At an average temperature of 16.5°C (typical of the 1945–1975 period), the sardine stock has almost no surplus production and cannot sustain a fishery. At a temperature of 17.3°C (typical of pre-1945 and post-1975 years), sustainable yield can potentially exceed 1 million tons annually, provided the parental abundance is at a biomass of about 2 million tons, a level that has not yet been achieved in the recent recovery. Except for a brief cooling period in 1999, Scripps Pier temperature continued to be warm through 2003 (Fig. A2.13).

Pacific sardine are a migratory species. When the northern sardine stock is large and ocean conditions are favorable, sardines migrate to British Columbia waters in the summer to feed. In

1947, the fishery on these summer migrants collapsed due to the complete absence of sardines in Canadian waters. After a 45-year absence from Canadian waters, sardines reappeared throughout the continental shelf waters off the WCVI in 1992. Research surveys indicated that their distribution from 1992–96 was limited to the southern part of Vancouver Island. In 1997, their distribution expanded northward and by 1998, sardines inhabited the waters throughout Hecate Strait (northern coast of British Columbia), located east of the Queen Charlotte Islands, and up to Dixon Entrance (southeast Alaska). Spawning was reported off the WCVI in 1997 and 1998. In 1999, following the El Niño, research surveys indicated that sardine distribution in Canadian waters contracted southward. By 2003, sardines did not appear in Canadian waters until late July and were confined to coastal inlets along Vancouver Island. The 2003 survey off Vancouver Island found virtually no sardines in the offshore waters, except in the south, and some concentrations at the mouth of the inlets.

#### **Gadids**

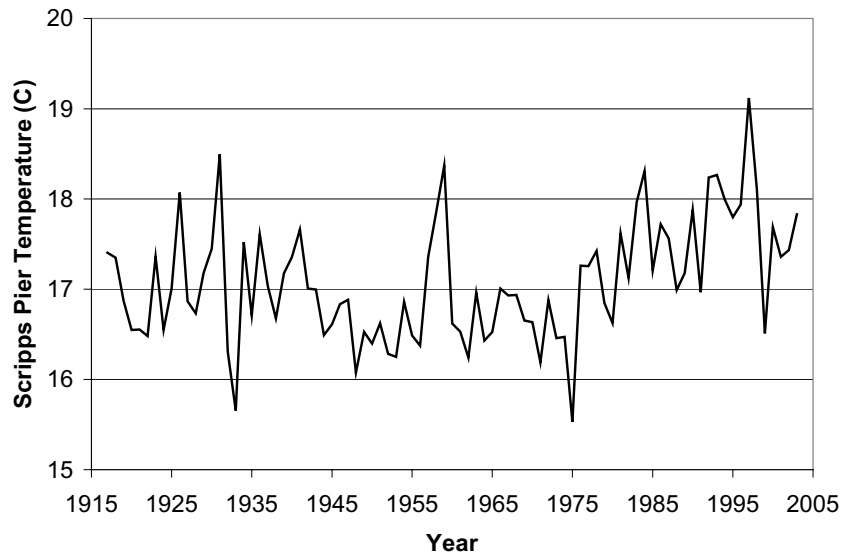
##### Pacific cod (*Gadus macrocephalus*)

Pacific cod are distributed throughout the coastal North Pacific, from Santa Monica, California, up through the Bering Sea and to the Sea of Japan. Growth is rapid within the first year, with Pacific cod reaching lengths of approximately 30 cm. Maximum recorded sizes exceed 100 cm, and estimated maximum age is 11 years (Westrheim 1996). Pacific cod recruit to the fishery at age 2 and a length of approximately 40 cm, and are fully mature at age 3, corresponding to approximately 50 cm (Westrheim 1996).

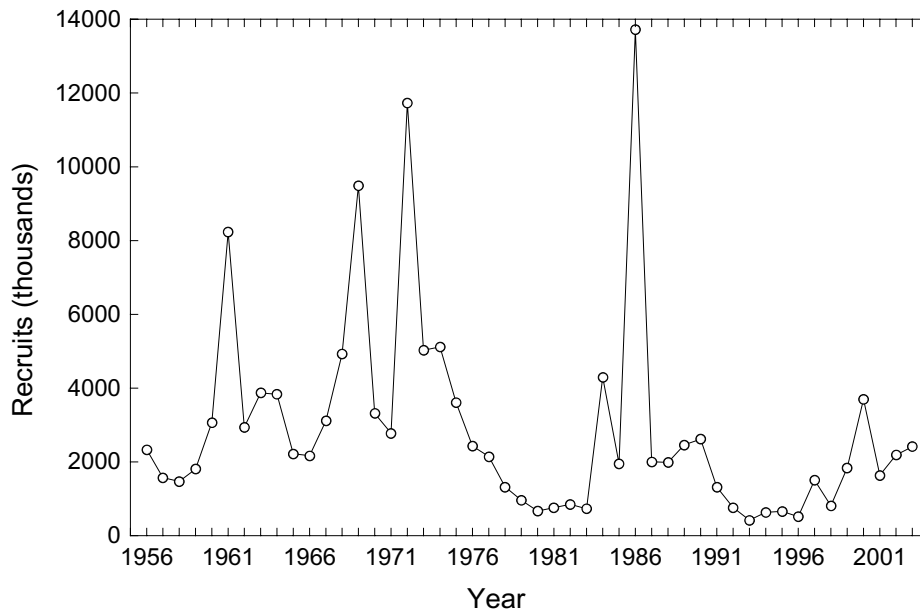
In British Columbia, there are four stocks defined for management purposes: Strait of Georgia, WCVI, Queen Charlotte Sound, and Hecate Strait. Though there are currently no genetic analyses to verify stock delineation, tagging studies indicate that there is very little movement of Pacific cod between these four areas (Westrheim 1996). The WCVI and the Hecate Strait stocks have historically supported commercial fisheries, and are the two stocks for which stock assessment information is available. Assessments on both stocks indicated a dramatic decline in biomass in

the 1990s, from historic high levels of abundance in the 1980s (Sinclair 2000; Sinclair *et al.* 2001; Starr *et al.* 2002). These declines were attributed to nine poor consecutive year classes, beginning in 1990 (DFO 1999). The WCVI stock is part of the

CCS. A delay-difference assessment model (Starr *et al.* 2002), which incorporates Pacific cod bycatch rates in a shrimp trawl survey, provides estimates of the number of recruits, which has remained at low levels since 1990 (Fig. A2.14).



**Fig. A2.13** Annual average sea surface temperatures (SSTs) measured at Scripps Pier, La Jolla, California.



**Fig. A2.14** Number of recruits (1000s of fish) of the west coast of Vancouver Island (WCVI) Pacific cod stock estimated by a delay-difference model (from Starr *et al.* 2002).

### Pacific hake (*Merluccius productus*)

Pacific hake range throughout the CCS, from Baja California to the Gulf of Alaska. Their distribution and abundance are closely linked to oceanographic conditions in the Northeast Pacific. The biomass, which is typically over 1 million tons, supports large domestic fisheries in both Canada and the United States.

Unusual juvenile and adult distribution patterns have been seen in the Pacific hake population since 1990. Juvenile distribution expanded northward from 1994–99. This was evident in the increased numbers of juveniles (ages 2 and 3) present in the Canadian fishery catches. In addition, an acoustic survey in 1998 off the Queen Charlotte Islands (northern British Columbia) observed numerous age-1 juveniles (1997 year class). During the 1990s, a greater proportion of the total mature population migrated into Canadian waters, and in some years were present in the Gulf of Alaska. Equally dramatic was the contraction of Pacific hake distribution in 2000 and 2001, with a low occurrence of Pacific hake off Canada. Information from a 2003 survey indicates a return to distribution patterns observed in the 1980s, with the northern limit of Pacific hake distribution at northern Vancouver Island (central British Columbia).

During the 1970s and 1980s, strong year classes in Pacific hake occurred every 3–4 years (1973, 1977, 1980, 1984, 1987, 1988). From 1989–98, there was only one strong year class of Pacific hake. Reflecting this, acoustic estimates of Pacific hake biomass declined steadily from the early 1990s, with the lowest observed biomass occurring in 2001 (738 thousand tons). In contrast, the 2003 biomass estimate (1.8 million tons) increased 120% over the 2001 survey estimate. The strong 1999 year class appeared as age-2 fish in the 2001 survey, and entered the mature population as age-4 fish in 2003. This isolated large year class is principally responsible for the increase in biomass estimated for 2003, and abundance is projected to decline over the next few years (Helser *et al.* 2004). This is the first above-average year class since the late 1980s.

### **Rockfish**

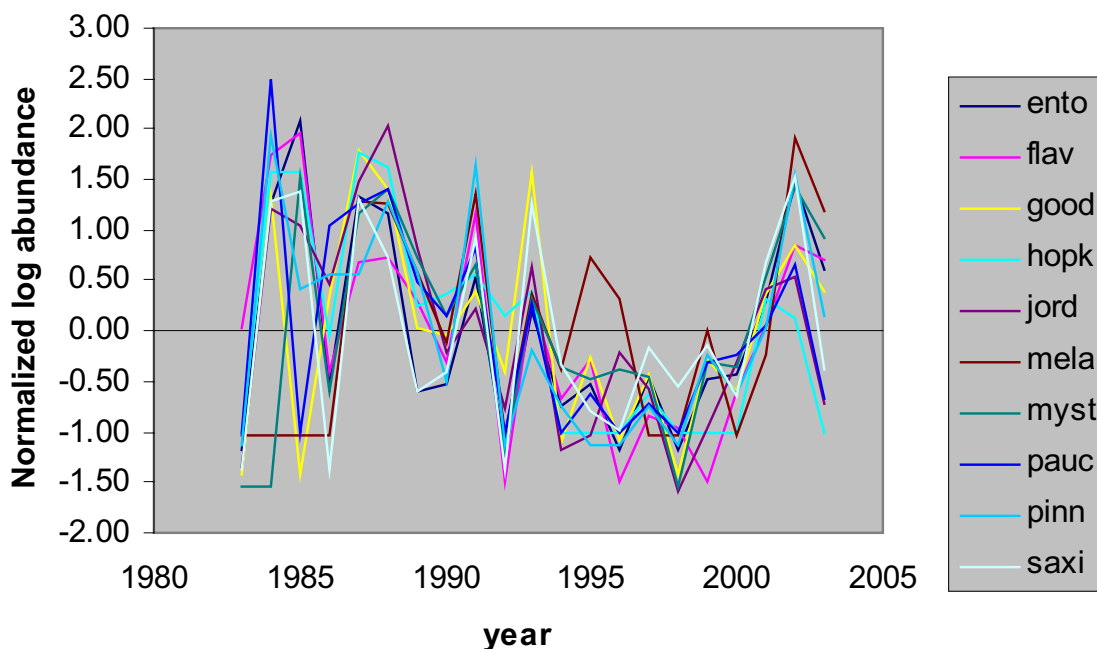
#### Juvenile rockfish (*Sebastes* spp.)

The abundance of juvenile rockfish has been monitored off the central California coast since 1983. In May and June of each year, the National Marine Fisheries Service Santa Cruz Laboratory conducts a month-long midwater trawl survey at standard stations (Ralston and Howard 1995), and annual abundance indices are derived by a delta-GLM (generalized linear model) approach using main effects of year, location and calendar date (Stefansson 1996). About ten species of rockfish are regularly encountered, three of which are not significantly exploited. The fish are sampled at an average age of about 100 days, near the end of their pelagic stage, and immediately prior to settlement. It is assumed that the principal life history events determining recruitment strength have been experienced by that age. Stock assessments of exploited species have confirmed that these juvenile abundances are well correlated with estimated recruitment strength. Because conventional fishery stock assessments are unable to estimate recruitment strength until a cohort is several years old and has entered the fishery, this juvenile rockfish survey provides information on recent recruitment patterns that would not otherwise be available for many years.

The poor recruitment experienced by many eastern Pacific groundfish species during the 1990s is shown clearly by the coherent decline of all ten rockfish species in the survey (Fig. A2.15). Catch rates of juvenile rockfish declined 1000-fold from 1988–98, a period of warming ocean temperatures. The pattern was shared by every species in the survey, including unexploited species. Several species were not encountered at all by the survey from 1996–98, and those zero values of catch rate cannot be plotted on the log scale of Figure A2.15. Abundance of juvenile rockfish did not recover immediately with the shift to cooler ocean temperatures in 1999 and 2000, although recent stock assessments show that some groundfish species, such as bocaccio (*S. paucispinis*) and lingcod (*Ophiodon elongatus*), produced unusually strong recruitment in 1999 (MacCall 2003; Jagielo *et al.* 2004). Abundance of juvenile rockfish

increased somewhat in 2001, and in 2002–04, has returned to levels similar to those seen in the 1980s. Survey results in the El Niño year of 2003

were lower than adjacent years, which is consistent with observations from previous El Niño years.



**Fig. A2.15** Fluctuations in abundance of juvenile rockfish off central California, as measured by catch rates in midwater trawls. Preliminary results for the 2004 survey appear similar to 2002.

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